Electron Cloud Effects at Positron/Electron (e+/e-) Machines and Electron Cloud Diagnostics

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Abstract. Background electrons are ubiquitous in high-intensity particle accelerators. Under certain operating conditions, amplification of the electron cloud can occur. The beam-cloud interaction can seriously degrade the accelerator performance with effects that range from vacuum degradation to collective beam instabilities. Although electron cloud effects (ECEs) were first observed 20 years ago in a proton ring, in recent years, they have been widely observed and intensely studied in e+/e- rings. This paper will focus on describing electron cloud diagnostics, which have led to an enhanced understanding of ECEs, especially details of beam-induced multipacting and saturation of the cloud. Such experimental results can be used to provide realistic limits on key input parameters for modeling efforts.

INTRODUCTION

Interactions between high-intensity particle beams and a background population of low-energy electrons, known as the electron cloud (EC), have been widely reported[1]. The mechanisms giving rise to the cloud vary[1,2], and in many cases, the cloud does not affect the beam. However, amplification of the cloud can occur under certain operating conditions, potentially giving rise to numerous effects that can seriously degrade accelerator performance. First observed in proton rings, electron cloud effects (ECEs) have in recent years been intensely studied in high-energy positron and electron rings as well. Mitigating ECEs remains an important concern in present and future high-intensity, high-energy accelerators.

An important tool in an improved understanding of ECEs has been the development of electron cloud diagnostics. Experimental data characterizing the EC properties can be used to provide realistic limits on key input parameters for modeling and analytical calculations. Combining EC and standard beam diagnostics allows EC effects to be separated from those arising from the geometric wake field. Although the nature of the beam-cloud interaction is rather different in positron vs. proton machines, there is a potential for synergy in the techniques applied to study the EC in both. This will be illustrated using results from the Advanced Photon Source (APS) at Argonne National Laboratory (ANL) and the Proton Storage Ring (PSR) at Los Alamos National Laboratory (LANL).

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OVERVIEW OF EC EFFECTS

Many comprehensive review papers can be found in the proceedings of recent U.S. and European Particle Accelerator Conferences, giving a summary of experimental observations and modeling of electron cloud effects[1]. Only the briefest of discussions is given here. We will focus on two phenomena observed in both APS and PSR: beam-induced multipacting (BIM) and the build-up and saturation of the cloud. BIM is a resonance condition that can lead to large amplification of the EC if the secondary electron emission coefficient (δ) of the chamber surface is greater than unity. BIM can also be responsible for vacuum degradation due to electron-stimulated gas desorption, first observed at the CERN proton Intersecting Storage Ring (ISR)[3]. Depending on machine conditions, the cloud density can be observed to either grow or remain constant over a bunch train (or several turns). In either case, the cloud density appears to eventually reach saturation at a level related, in some cases nonlinearly, to the average beam charge density.

At APS[4], EC amplification and associated pressure rise due to BIM were clearly observed with positron beams at certain bunch currents and spacings (the Al vacuum chambers have a relatively high δ). A more modest effect is observed with electron beams in present APS operation. At BIM conditions, the cloud density saturates after 20-30 bunches. With positron beams only, a horizontal coupled-bunch instability was observed at conditions coinciding with the maximum saturated cloud density. At PSR[5], a long observed e-p instability occurs at a threshold bunch intensity and buncher voltage. BIM is observed on the trailing edge (tail) of the bunch, but these prompt electrons appear to have a less direct relationship to the instability. On the other hand, electrons that survive the gap are observed to saturate near the instability threshold.

ELECTRON CLOUD DIAGNOSTICS

The planar retarding-field analyzer (RFA), first developed and implemented at APS[6], is a very simple device that measures electrons colliding with the chamber wall. The RFA consists of two grids and a graphite-coated collector (to lower its δ). The outer grid is grounded, while the inner grid can be biased for electron energy selection. The RFA is an integrating device; differentiating the collector signal gives the EC energy distribution. Figure 1 shows a schematic of two RFAs mounted on a standard APS chamber.

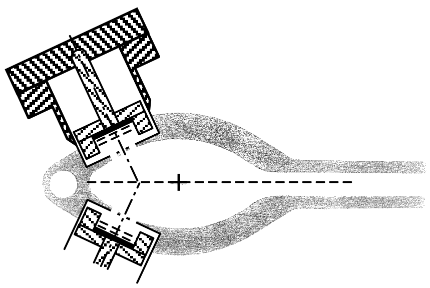

FIGURE 1: ANL schematic of two RFAs mounted on a standard APS chamber, cross-sectional view (42 × 21 mm chamber half-dimensions).

The benefit of shielding the collector and bias grid is that the measurement does not disturb the EC in the chamber. It is very difficult to measure the true wall flux or energy distribution with a biased beam position monitor (BPM), illustrated in Fig. 2. Secondary electron emission from the BPM surface affects the wall flux (the signal can even change sign). Also, the BPM bias changes the collection length (i.e., volume).

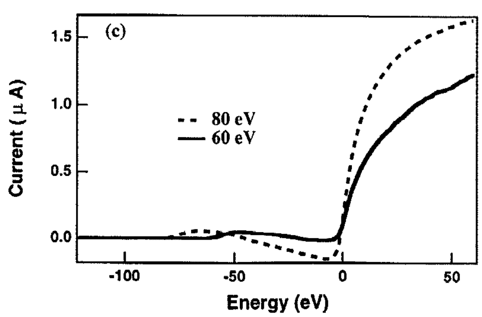

FIGURE 2: Signal produced from a BPM irradiated by 60-eV and 80-eV electrons as a function of bias voltage applied to the BPM[6].

ANL-type RFA devices have been widely implemented: Intense Pulsed Neutron Source (ANL), PSR (LANL), Beijing Electron-Positron Collider (IHEP), KEK B-factory (KEK), Super Proton Synchrotron (CERN), and Alternating Gradient Synchrotron booster (BNL). At PSR, the RFA was augmented with a broadband amplifier to allow time-resolved measurements. Also at PSR, the effect of chamber surface coatings with lower δ was measured *in situ*. At APS and PSR, RFAs were installed in regions free from external magnetic fields. At CERN SPS, an RFA-based detector was installed inside a specially-constructed dipole magnet, and multi-strip collector electrodes measure the transverse EC spatial density[7].

To detect electrons in the gap after the bunch passage, an electron sweeper was developed at PSR[8]. A curved electrode subtending a half-angle of 75º (~40 cm long) is placed opposite a large-aperture RFA (~8× higher sensitivity than the original design), shown in Fig. 3. A short (~20 ns), ~500 V pulse on the electrode selects the sampling time in the gap; the fractional acceptance area of electrons swept into the RFA is 0.3.

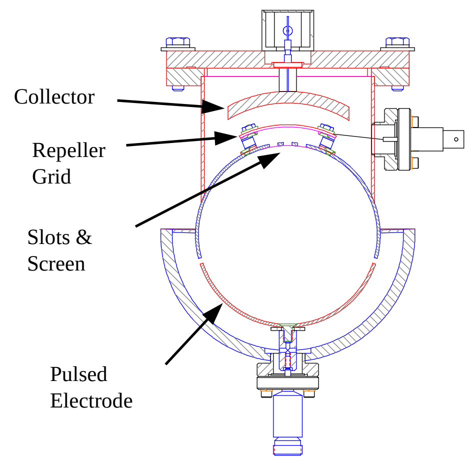

FIGURE 3: LANL electron sweeper (chamber diam. 10 cm).

A number of EC diagnostics concepts have been proposed or are under development, either for better energy resolution (Bessel Box at APS)[9], or less perturbative detection of the electrons in the vacuum chamber (e.g., by G. Lambertson (LBNL) and S. Heifets (SLAC)). At KEKB, the EC density is inferred indirectly by comparing the bunch-by-bunch space-charge tune shift with and without the EC.

EC MEASUREMENTS AT APS

In experiments[4] where the bunch spacing was varied, the primary (photoelectron) vs. secondary components of the EC production processes could be separated. While the RFA only measures the electron wall flux, analysis of the EC energy spectra gives an indirect measure of the electrons near the beam; a high-energy tail results from electrons near the beam that are accelerated to higher energy. The BIM resonance at 7 λ_{rf} and variation in EC distributions can be seen in Fig. 4. The collector current I_c is differentiated with respect to the bias voltage and normalized to the total beam current I_b. In Fig. 5, the measured EC build-up and saturation over positron bunch trains at the BIM bunch spacing is shown as a function of bunch current.

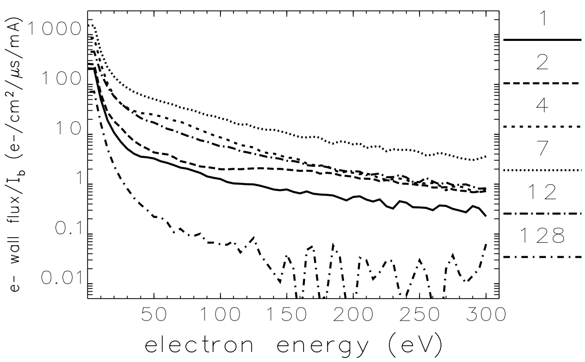

FIGURE 4: EC energy distribution vs. bunch spacing (units of rf wavelength, λ_{rf}); 2 mA/bunch, 10 positron bunches.

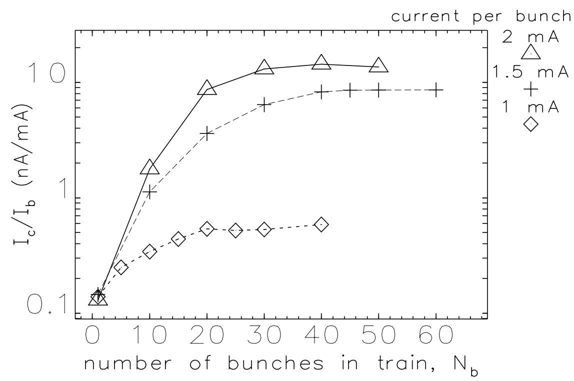

FIGURE 5: Measured EC build-up and saturation over positron bunch trains at the BIM bunch spacing. A horizontal coupled-bunch instability occurs for trains longer than ~20 bunches with a threshold current of about 2 mA/bunch.

EC MEASUREMENTS AT PSR

Extensive measurements have been carried out at PSR[5] to study the EC properties and correlation with the e-p instability. The electron sweeper data are particularly interesting; a typical result is shown in Fig. 6. The machine conditions are: 7.7 µC/pulse and 280-ns bunch length. BIM on the trailing edge of the beam accelerates and amplifies electrons that strike the wall near the peak and in the tail of the bunch. These prompt electrons are believed responsible for populating the gap but the relationship is nonlinear. The electrons swept from the gap are more nearly linear with beam current for intensities in the region of greatest interest (> 4 µC/pulse) and saturate at 1-2% average beam neutralization near the instability onset.

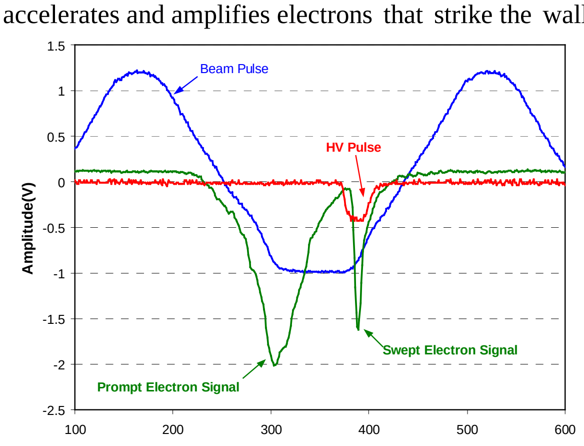

FIGURE 6: Typical PSR electron sweeper data (sweeper 500 V, RFA bias voltage –25 V, 32 macropulses averaged).

SUMMARY

Electron cloud diagnostics based on the planar RFA have been successfully and broadly applied to study the EC properties and dynamics in positron, electron, and proton rings. The EC energy distribution (for flux at the wall) and estimate of density can be extracted from the RFA spectra – this is not possible with biased BPMs or collecting plates. EC diagnostics to date are mostly limited to electrons collected at the wall or swept to the wall. A number of concepts to measure the cloud nondestructively within the vacuum chamber have been proposed but not yet implemented.

Despite the obvious differences in the beam-cloud interaction, there is likely to be synergy between proton and positron rings in understanding the mechanisms of EC saturation and the correlation with cloud-induced instability thresholds. More analyses and experiments are planned.

ACKNOWLEDGMENTS

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